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ELECTRO-SPARK EXTRUDING

J.H. WAGNER

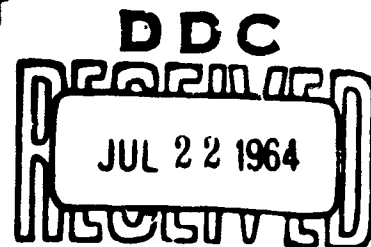
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INTERIM PROGRESS REPORT

1 APRIL 1964 to 1 JULY 1964



The general design criteria of working pressure, pressure source, shock loading and preliminary requirements of a 200,000 psi pressure vessel are formulated. Design information for the 30" O. D. x 6" I. D. vessel is presented. A 200,000 psi pressure pumping system and associated high pressure fluids are presented.

BASIC INDUSTRY BRANCH
MANUFACTURING TECHNOLOGY LABORATORY

AERONAUTICAL SYSTEMS DIVISION
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

ELECTRO-SPARK EXTRUDING

J. H. Wagner

Republic Aviation Corporation
Manufacturing Research Department

Contract AF33(657)11265
ASD Project 8-111

Interim Technical Engineering Report No. 4
1 April 1964 - 1 July 1964

Republic Aviation Corporation Report No. RAC 2491

The design aspects and pressure vessel details are discussed for a device to use capacitor discharge energy to extrude from a 200,000 psi hydrostatic fluid medium. A 200,000 psi, 20 cubic inch per minute pump is described.

BASIC INDUSTRY BRANCH
MANUFACTURING TECHNOLOGY LABORATORY
Aeronautical Systems Division (AFSC)
United States Air Force
Wright-Patterson Air Force Base, Ohio

ABSTRACT-SUMMARY
Interim Technical
Progress Report No. 4

ASD INTERIM REPORT 8-111 (IV)
July, 1964

ELECTRO-SPARK EXTRUDING

J. H. Wagner

Republic Aviation Corporation

General design criteria consisting of working pressure, pressure source, shock loading and preliminary specifications of a pressure vessel to perform capacitor discharge extrusion from a 200,000 psi fluid pressure are discussed. Design criteria for the container, liner, insert and die assembly components are presented. A pumping system to obtain pressures to 200,000 psi with inhibited water is described. Fluids for use at pressures from 0 to 200,000 psi are proposed. Shielding of equipment and other safety considerations in working with ultra-high pressures are outlined.

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FOREWORD

This Interim Technical Progress Report covers the work performed under Contract AF33(657)11265 from April 1, 1964 to July 1, 1964. It is published for technical information only and does not necessarily represent the recommendations, conclusions or approval of the Air Force.

Mr. J. H. Wagner of the Manufacturing Research Department, Republic Aviation Corporation is the engineer in charge of the project. Mr. Gunther Pfanner is cooperating in the research.

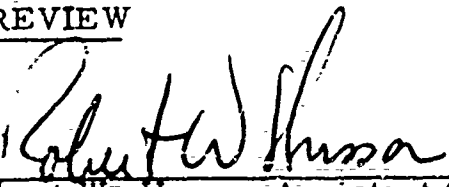
Mr. D. H. Newhall of the Harwood Engineering Company, Walpole, Massachusetts, has designed the pressure vessel to be used in the program.

The primary objective of the Air Force Manufacturing Methods Program is to increase producibility, and to improve the quality and efficiency of fabrication of aircraft, missiles and components thereof. This report is being disseminated in order that methods and/or equipment developed may be used throughout industry, thereby reducing costs and giving "MORE AIR FORCE PER DOLLAR."

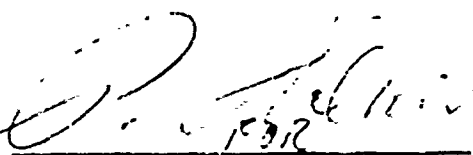
Your comments are solicited on the potential utilization of the information contained herein as applied to your present or future production programs. Suggestions concerning additional manufacturing methods development required on this or other subjects will be appreciated.

PUBLICATION REVIEW

Approved by:


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T. F. Imholz, Chief
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INTRODUCTION

Electro-spark extrusion is a metalforming concept involving recovery of the energy derived from a rapid discharge of capacitor stored electrical power by reduction of a metal billet through an appropriate die. One method, the electrohydraulic reduction of the billet, places the extrudable material in an ultra-high pressure fluid environment with the rapid energy discharge occurring across a suitable electrode gap. This short time duration gap discharge in a properly designed high strength container causes a shock-pressure wave to strike the billet face and, upon reflection, to initiate particle acceleration in the billet material and to release to the billet face some of the intrinsic kinetic and pressure energy available as consequence of known wave reflection parameters. The sum of these phenomena when added to the potential energy present in the high fluid pressure environment have been shown by mathematical analysis to be ample under carefully controlled conditions to cause a metal billet to yield and to extrude a given length for the time duration of one electrical pulse. The problem of maintaining extrusion then, properly becomes one of providing sufficient discrete pulse discharges with the correct time interval to allow a constant velocity extrusion.

In addition, the capacitor discharge equipment can be alternately employed to produce impulsive electromagnetic forces upon the billet in the hydrostatic container. In this method, the rapid discharge of the stored electrical energy produced high magnetic fields about an appropriately constructed conductive coil. By induction, to a conductive piston-disc interposed between the coil and the billet, repulsive magnetic forces rapidly accelerate the disc and thereby drive a pressure wave against the billet.

As an alternative, where the billet material is sufficiently conductive, the electromagnetic repulsion may be coupled to the billet face directly in order to induce the acceleration forces required to extrude the billet.

A third method of capacitor stored energy utilization is to recover the energy created by the electrohydraulic discharge and to transfer it by mechanical means to the billet. Displacement of the billet is accomplished

mechanically by the use of a piston-ram on the billet material in a suitable container. The pressure pulse or electromagnetic energy created by a series of discharges impinges on the face of the piston causing it to move forward to extrude the billet.

The advantages offered by the foregoing approach to electrohydraulic extrusion are: (1) elimination of billet container wall friction, (2) reduction of billet die surface friction, (3) creation of pressures considerably beyond those obtained hydrostatically, (4) reduced container size and cost.

To determine the production potential for extruding a steel alloy by the use of capacitor stored energy, the Aeronautical Systems Division of Wright Patterson Air Force Base has awarded Contract No. AF33(657)11265 to Republic Aviation Corporation. Extrusion will be attempted in the course of the program by conducting experiments with capacitor discharge equipment to develop the most suitable techniques for metal reduction by several electrohydraulic methods. The program consists of two phases as follows:

- Phase I - Design of the Extrusion Equipment
- Phase II - Development of the Extrusion Process

The approaches mentioned in the foregoing are to be thoroughly investigated for suitability toward attaining the objectives of the program; i. e., extrusion of a 2 inch diameter to a 1/4 inch round.

Having evaluated vendor proposals with regard to cost and conformance to specifications, this contractor with the approval of the Air Force selected the Harwood Engineering Company, Walpole, Massachusetts as subcontractor for the extrusion equipment on Contract AF33(657)11265. Harwood Engineering, known for their achievements in the design and manufacture of ultra-high pressure equipment, have furnished specialized equipment to government agencies and private industry alike.

The Harwood proposal included the development of the engineering and design required for the fabrication of the experimental pressure vessel to contain 200,000 psi hydrostatic pressure. In addition, a pumping unit to supply inhibited water at 200,000 psi and to displace 20 in³ per minute is to be manufactured for use with the extrusion device.

Engineering and design work have been completed. The salient points in the design are presented in this report.

As the pumping equipment is a standard DA-10, manufactured by Harwood Engineering company, assembly was begun at the same time the engineering on the vessel was being done. This unit has been delivered to Republic Aviation and is presently being installed.

PRESSURE VESSEL DESIGN

Basic Equipment Design

The concept of electrohydraulic extrusion calls for the reduction of a billet through a die from an ultra-high (up to 200,000 psi) fluid pressure by use of the potential energy available from the compressed liquid, and by recovery of the energy released from an instantaneous discharge of capacitor stored power across a suitable gap. The requirement to contain a pressure of a high order, to insert an electrode into the high pressure medium, and to contain the dynamic forces anticipated from the capacitor discharge presents a problem so different from the conventional, that immediate solutions are not readily found in the literature. For this reason, before design was started, analysis and derivation of the governing relationships⁽⁴⁾ had to be achieved with respect to shock loading on a vessel containing a high order of internal hydrostatic pressure.

Specifications for the equipment to be used in the program are based on considerations of the desired working pressure, the method of attaining the given pressure and the effects of shock loading in a statically designed container.

Working Pressure - The extrusion pressure vessel must contain a high hydrostatic pressure and be capable of withstanding shock loads imposed by the explosive effects of a capacitor discharge. The extrusion equation $P = \rho \ln \sigma$ where ρ , the resistance to deformation and σ the extrusion ratio is used to gain an insight as to the order of pressure required to extrude 4340 steel at a 64:1 reduction ratio. If for 4340 steel, $\rho = 125,000$ psi⁽⁵⁾ and $\sigma = 64:1$, the pressure calculated to extrude is 520,000 psi. These fluid pressures, of course, are completely unobtainable and the problem becomes one of selection of a reasonable working pressure and using the capacitor discharge to obtain the balance of the energy for extrusion.

Pressures above 250,000 psi are in the ultra high pressure range for which container sizes are one to six cubic inches and seals are frequently effected only by encasing the specimen in a frangible lava block. On the other hand, pressures less than 250,000 can quite readily be attained in

vessel sizes adequate for experimental extrusion with known seal and vessel design criteria. Based on these factors, decision was made to design to a working pressure of 200,000 psi.

Pressure Source

The generation of 200,000 psi in the pressure vessel can be obtained by either modification of a suitable hydraulic press whereby the ram of the press acts to generate the pressure in an open ended vessel or by utilizing a fully closed pressure vessel in which the pressure is generated by direct fluid flow from a pump and intensifier system. The advantages and disadvantages of the two systems are discussed below.

	<u>Press</u>	<u>Pump</u>
Location	- Fixed - must move capacitor discharge installation to press	Portable - can be moved to capacitor discharge location
Pressure Capacity	- 250,000 psi appears to be top of state-of-art in practical sizes for extrusion due to strength requirements of vessel	Same
Ability to Maintain Extrusion	- Pressure can be maintained in vessel by advancement of ram. No problem in maintaining 200,000 psi selected hydrostatic pressure during time cycle required for delivering the anticipated capacitor discharge energy.	At 200,000 psi, a flow rate of 180 in ³ /min can be obtained. The selected flow rate of 20 in ³ /min. is more than sufficient to maintain pressure in the vessel during the complete extrusion of target shape.

- Cost - Modification of an existing press would be less costly than procurement of a pump and intensifier system. However, the cost of relocating the capacitor discharge installation to the press would have to be added to the press modification cost so that the cost differential would be considerably narrowed. In addition, if the installation is considered permanent, the current value of the press must be added to this cost. A temporary installation would entail the disassembly and relocation of the capacitor discharge installation. Finally, the cost of providing adequate safety features around the press which would normally be in a production environment would be higher than the cost involved in isolating a pump and intensifier system.

Consideration of the forgoing arguments determined the selection of a pump and intensifier system to generate the 200,000 psi hydrostatic pressure. This conclusion also fixed the geometry of the pressure vessel. A closed end vessel is required for use with a pumping system.

Preliminary Design Specifications - Having determined the working pressures and the method of pressurizing the pressure vessel, a tentative design specification was outlined and a container geometry based on static considerations was proposed. The established specifications were:

- | | | |
|----------------------|---|---|
| Vessel size | - | 24" O. D. x 60" long
2 1/2" I. D. x 26" working length |
| Vessel Construction | - | A single shrink shroud of 4340 steel over a 250,000 psi maraging steel liner |
| Hydrostatic Pressure | - | 200,000 psi |
| Hydraulic Flow Rate | - | 20 in ³ /min. at 200,000 psi |
| Capacitor Discharge | - | Device to incorporate 5/8" diameter electrode and accommodate discharges of 155,000 joules (9611 uf at 18,000 volts). |

Accessibility - Vessel to be double ended. One closure is to contain an extrusion die and shall be accessible for examination and replacement of the die. The other closure contains the electrode and pressure port and is to be accessible for examination and replacement of the electrode spark gap.

Effect of Shock Loading - The derived equations of state (4) were applied to the container geometry outlined in the foregoing, in order to check the integrity of the proposed design under the combined hydrostatic and detonative internal loadings.

The design check indicated that a pressure vessel loaded internally with hydrostatic pressure of 200,000 psi and subjected to the dynamic forces created from an explosive discharge would experience severe plastic metal deformation (strain) from the 2 1/2 inch diameter outward for a radial distance somewhat less than 2 inches. At a diameter of six inches ($r = 3''$) the effects of the shock loading are attenuated to the degree that the metal in the wall of the container responds to the impulsive load in an elastic manner.

If the inside diameter of the vessel is increased to six inches and the outside diameter expanded proportionally, the severity of the shock wave is reduced at the fluid metal interface ($r=3''$) but not materially diminished below the critical value indicated for the onset of plastic strain.

The particle velocity in a transient wave has been shown to be a measure of the severity of the effects of a shock on a fluid or metal (4). The particle velocity is given by the relationship, $u = \frac{P}{\rho c}$ where P is the pressure of a shock wave upon reflection at an interface and ρ the density, and c the acoustic velocity. The ρc product for steel is 117,000 and for water is 5,000. The initial particle velocity in steel is 1/23 of the value in water, thus indicating that a steel insert interposed between the detonation and working diameter ($2r=6''$) of the pressure vessel serves to attenuate the effects of particle velocity to the degree that the detonative event does not seriously affect the behavior of the container wall already statically stressed.

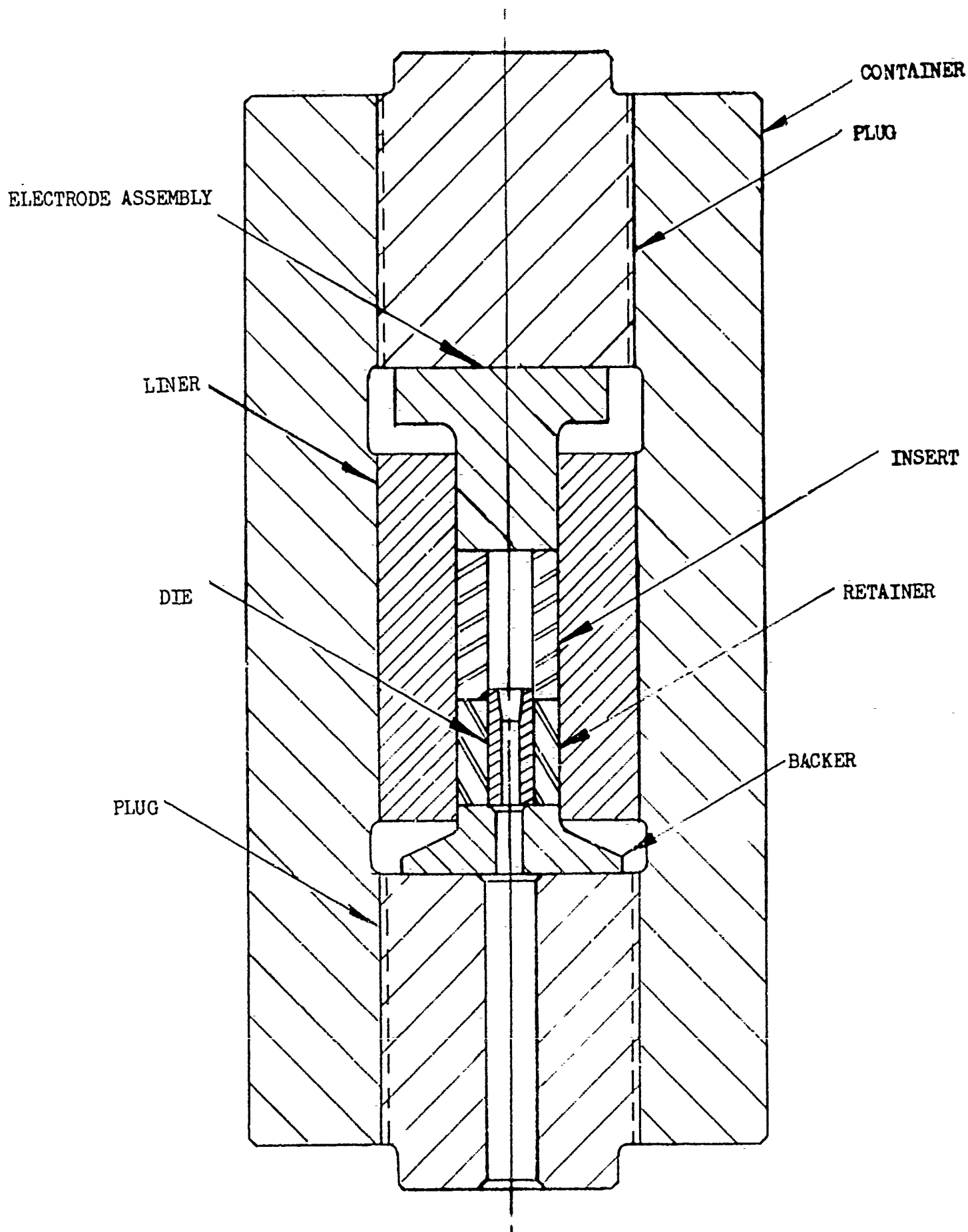


FIGURE 1
PRESSURE VESSEL CONSTRUCTION

Because the steel liner undergoes severe plastic deformations at the bore ($r = 1''$) and because attenuation of the particle velocity $r = 3$ inches results in elastic behavior at that point, decision was made to design into this volume a replaceable insert so that, after an undetermined number of shock applications when severe deformation was detected, the liner can be replaced.

Pressure Vessel Construction

The basic pressure vessel equipment, Figure 1 has been designed by the Harwood Engineering Company. It consists of a vessel of single shrink construction with a shroud fitted over a liner. The bore of the vessel contains a replaceable insert. Closure is provided by threaded plugs at each end. A die and retainer is incorporated in one end of the vessel while an electrode, spark gap assembly and means for the insertion of pressure is included in the opposite end.

The dimension and materials used in the main components are tabulated in the following. The dimensions differ from those presented in the Preliminary Design Considerations, because the vessel working diameter was increased from two inches to six inches.

<u>Item</u>	<u>O. D.</u>	<u>I. D.</u>	<u>Length</u>	<u>Material</u>
Container	30"	15"	60"	E4340 vacuum degassed steel
Liner	15"	6"	21"	Vascomax 250 marage steel
Insert	6"	2 1/4"	8 1/2"	Vascomax 250 marage steel
Plugs	15 1/2	-	15 1/2	E4340 vacuum degassed steel

Insert - Once decision was made to use a replaceable insert, the problem is one of design. One requirement obtained from the stress analysis was to have the liner under equiaxed restraint when it received the full force of a detonation. To satisfy the necessity for equal loading, the liner is designed so that the pressurized fluid in the six inch bore of the pressure vessel completely encompasses it. (Figure 2). The insert is "flanged" in both ends with longitudinal and radial paths cut for the passage of fluid. The flanged portion is 1/16 inch larger in diameter than the body of the insert. The bore of the insert will register on the spark gap electrode on one end. The die will register on the other in order to prevent loose fittings from the volume reduction under high fluid pressure.

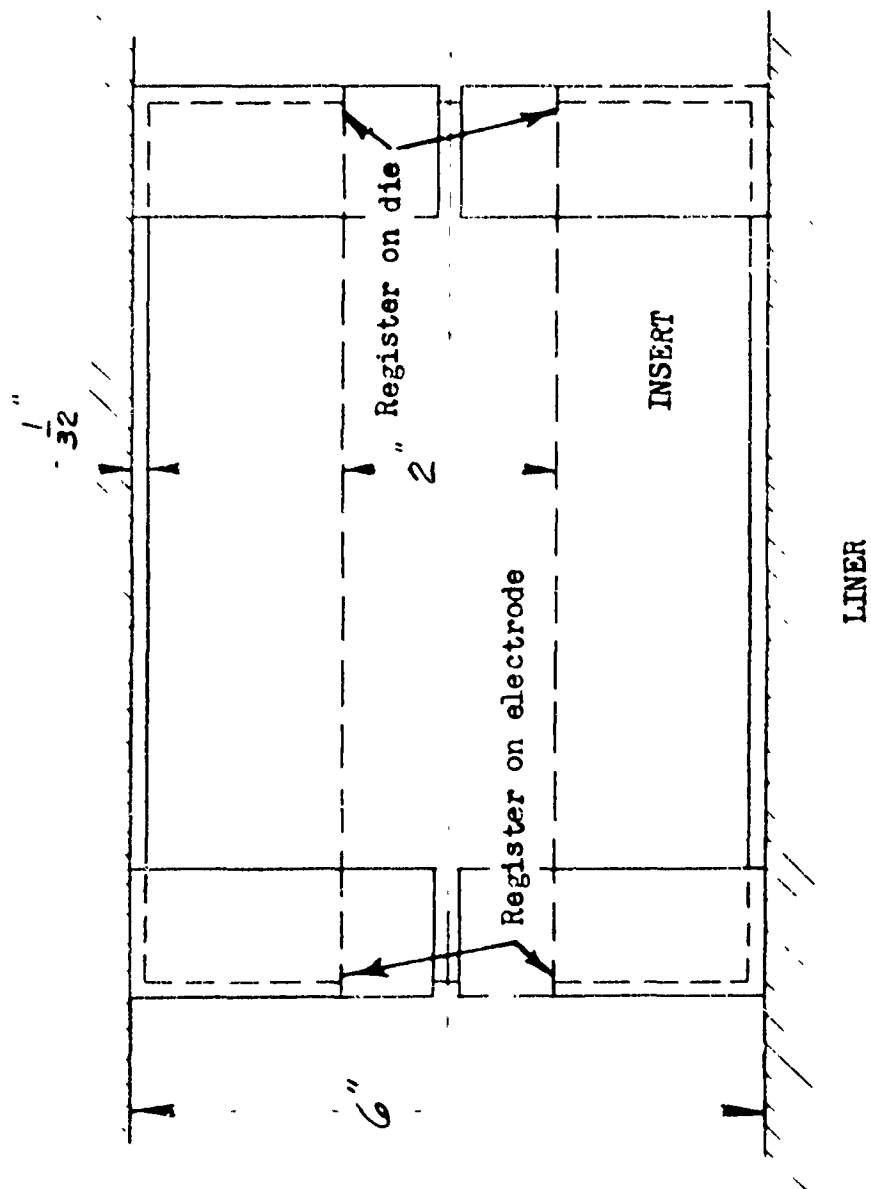


FIGURE 2
REPLACABLE LINER

Die and Retainer - The die and retainer assembly with backer are shown in Figure 3. Shown in place of the die is a blank plug to be used for testing of the vessel at working pressure. The retainer and die seat on the backer which bears in the threaded plug face. Seals are provided both at the retainer O. D. and die O. D. The materials used in these components are as follows: retainer, 4340 steel; die HTB-2 steel; backer, an S-7 tool steel.

Seals - The seals used in the pressure vessel to close off pressure are a proprietary item from Harwood Engineering Company, using the unsupported area principle. They are shown in Figure (3) and consist of steel rings, leather packing, rubber "O" rings and a soft steel vee ring for the unsupported area. The assembly is held in place by a spring steel retaining ring.

In the design of the vessel, all packings have been placed behind some component to be out of the direct path of shock wave.

Electrode - The electrode assembly has presented some of the most difficult problems in the design of the extrusion device. Design of the electrode has just been completed as this report was being written. Because of their complexity, the details are not to be included at this time.

Status of Vendor Work - All preliminary engineering, dynamic and static stress analyses have been completed by Harwood Engineering Company and Republic Aviation. The assembly drawings and details of the long lead time components (container, liner, insert and plugs) were completed just so that orders could be placed for these basic items. Having done this, the balance of the detail drawings have been completed by the vendor. (There are about seventy items in the completed design, taking up considerable time in detailing and checking). At the present time, all components have been released for manufacture.

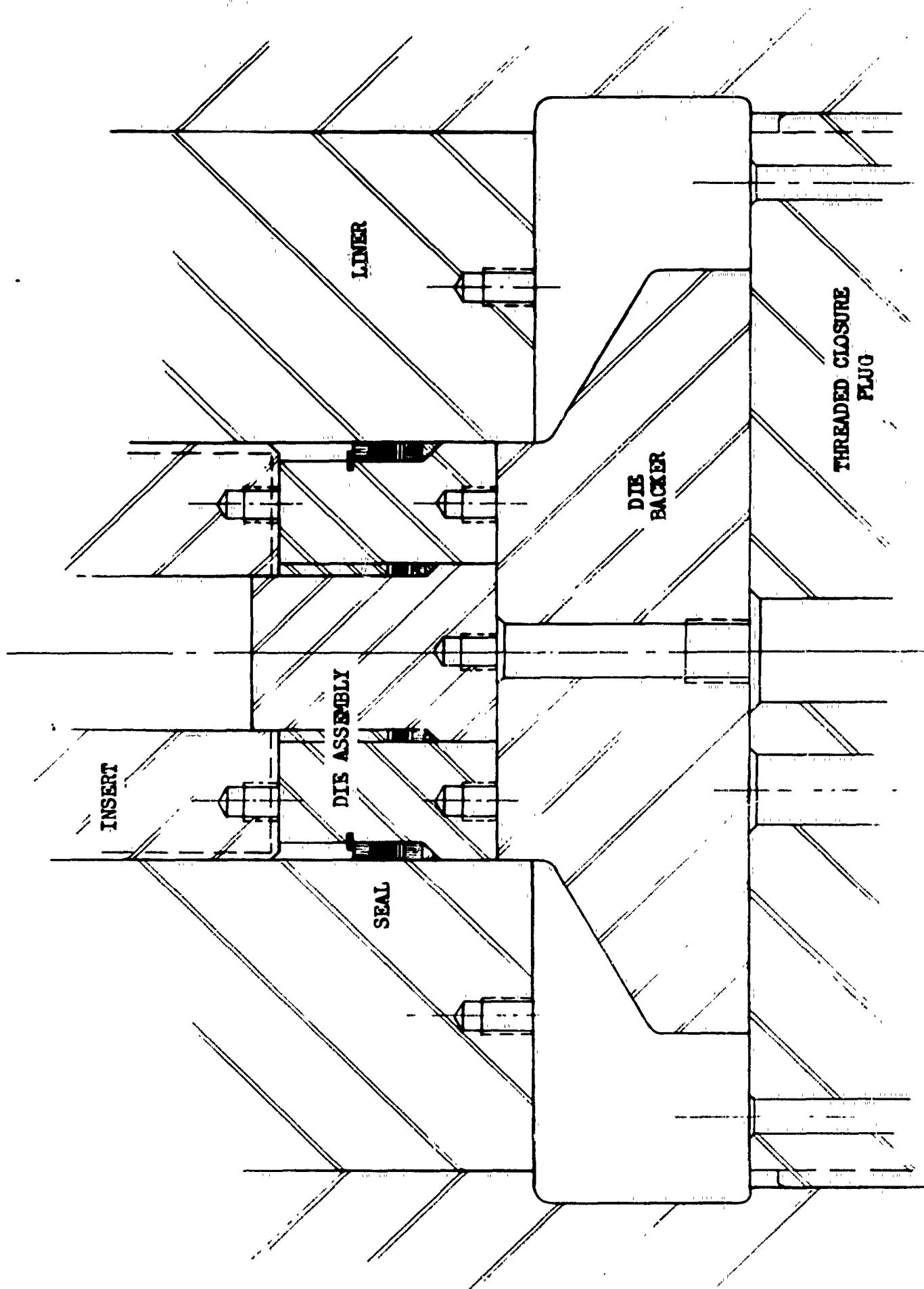


FIGURE 3
DIE ASSEMBLY DETAILS

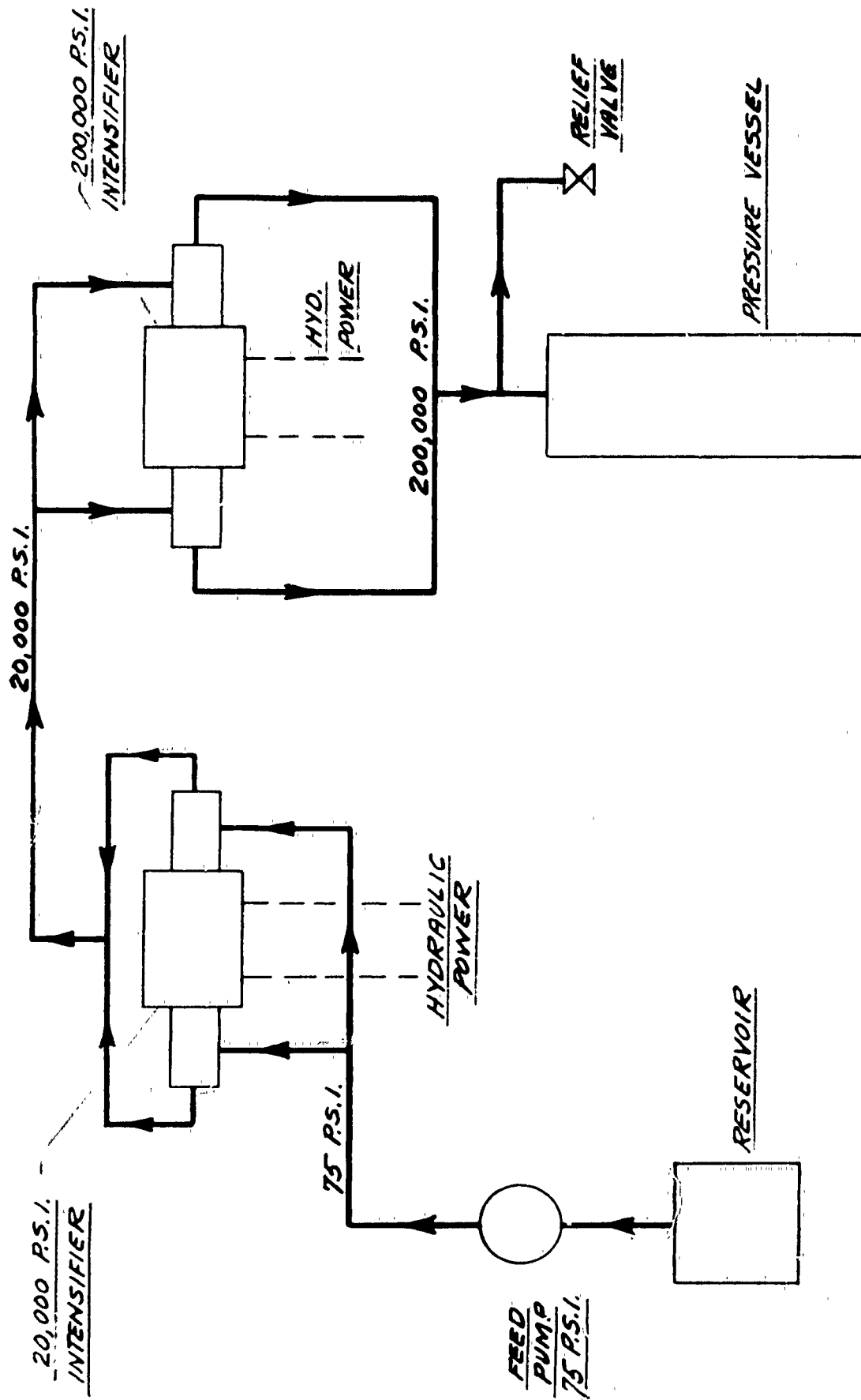


FIGURE 4
200,000 PSI PUMPING SYSTEM

HIGH PRESSURE PUMPING SYSTEM

Description of the Equipment

The Harwood Engineering Company DA-10 pumping system (3) purchased for this program is capable of generating fluid pressures up to 200,000 psi with a water inhibited fluid at a continuous displacement of 20 cubic inches per minute. The main components of the system are the high pressure pump, charging pump, feed pump and a hydraulic system for powering and controlling the two intensifiers.

Intensifier - The high pressure pump is an intensifier type capable of discharge pressures up to 200,000 psi. The ratio of areas used in the intensifier is 121/1 with hydraulic power supplied at 1,920 psi. The low pressure piston is directly aligned to a small high pressure piston and serves to drive it. The intensifier is double acting thus maintaining a discharge that is almost continuous into the pressure vessel. Friction and hydraulic losses amount to 5 to 10%.

Charging Pump - The charging pump, a smaller double acting intensifier type supplies liquid to the main intensifier. The pressure of the supply fluid is 20,000 psi maximum and is the resultant of an intensifier ratio of 12.2/1. The hydraulic pressure to drive this unit at maximum output is 1,800 psi including an allowance of 10% for friction and other losses. The displacement rate at the output end is 1.85 cubic inches per minute at 20,000 psi.

Feed Pump - A turbine type feed pump is used to supply the liquid to the charging pump. This pump operates at 75 psi and has an output capacity at this pressure of 75 gallons per minute (gpm).

Hydraulic System - Separate hydraulic systems are used for powering and controlling the two intensifiers. Included in this system are safety devices, interlocks and controls for either manual or semi-automatic operation. In semi automatic operation of the system, the fluid is raised to a pre-determined pressure level, held there and then through a timer and electrical relay, released through a power operated valve back to the reservoir.

The hydraulic pump for the 200,000 psi intensifier has a maximum capacity of 14.0 gpm at no load and 12.8 at load. It requires 17.9 horsepower to drive this unit. The hydraulic pump for the low pressure intensifier has a maximum capacity at no load of 3.3 gpm and 2.0 gpm at full load. It takes 4.2 hp to drive this unit.

Control of the high pressure discharge is attained by means of the hydraulic driving system. This system consists of a motor driven hydraulic pump and means for reversing the flow in the low pressure end of the intensifier. The hydraulic pump is protected by a pressure relief valve. The rate of pumping is controlled by a flow control in the main line of the hydraulic pump.

Safety Considerations

The acquisition and installation of the DA-10 pumping system requires that consideration be given to the hazards involved with the 200,000 psi intensifier and piping system used to carry the high pressure fluid to the pressure vessel. At the present time, a comprehensive study and protective equipment designs are being made to safeguard personnel working in the area of the pressure vessel and high pressure pumping system. The considerations presented are based on a preliminary study and further details will be presented as they are developed.

In a general sense, the hazards involved with any system storing a volume of ultra-high pressure fluid is proportional to the energy stored. Thus, the higher the pressure and the volume stored, the greater is the

hazard presented. It is almost axiomatic that the higher the pressures achieved, the more it becomes necessary to compromise the factors of safety in view of the high level of stress introduced in the equipment by the containment of super pressures.

The following general principles can be used as a guide in making the equipment and working area safe in view of the high order of potential energy being contained.

1. Appropriate barricading should be provided to isolate the hazardous part of the system. In the case of the pumping system, this is the high pressure end of the intensifier and the transmission lines to the pressure vessel, while the pressure vessel itself requires an enclosure to isolate it from working personnel in the area.

2. Reasonable rules of safety should be established and maintained.

Controls should be remotely located.

Piping joints should not be opened under pressure.

Personnel should be kept out of the line of fire of dead end plugs, frangible discs, etc.

Long lengths of pipe should be anchored and properly shielded so they do not whip if a connection fails or parts.

Full use of localized protection such as steel plate, ballistic pendulum devices and mechanically drawn tubing for protection should be used.

All personnel except operating personnel should be kept well out of the area when the equipment is in operation. A stray hydraulic leak at 200,000 psi can penetrate flesh instantly. In addition the heat generated in a fluid from a pinhole leak can cause severe burns.

High Pressure Fluids

The fluid to be pumped to high pressure will have to meet exacting and sometimes conflicting requirements, (1), (2), (3), which at very high pressures are seldom able to be satisfied wholly. Therefore, a compromise

is generally necessary. This has been found to be the case when reviewing the fluids available for use with electro hydraulic extrusion. The choice has narrowed to a very selective few. Some of the more familiar requirements are presented in the following:

1. The fluid should be relatively non-compressible. Although liquids are generally thought to be non-compressible, most of them shrink greatly under pressure, from 90 to 200 times as much as steel. (water, for example, at 100,000 psi compresses 16% of its free volume.) In all liquids, the rate of compression grows progressively less as pressure increases and this is accompanied by an increase in density or specific weight, and viscosity.

2. The liquid used must stay fluid at the high pressure. All liquids increase in viscosity more or less proportionately as they are compressed to greater density. The general rule is that the more complicated the molecule, the more likely to be an increase in viscosity with pressure. Since fluidity (the inverse of viscosity) is necessary, not only to free flow, but also to rapid transmittal of pressure, high viscosity is always an objectionable quality.

3. The liquid must not solidify as all liquids do freeze at some high pressure. This phenomena is also is also sensitive to temperature. These liquids freezing at low atmosphere temperatures usually freeze at the higher pressures. This freezing at pressure eliminates many fluids from consideration.

4. The fluid should be fire resistant or have a high flash point. Any leak from a high pressure system generates heat when combined with atomized fluid causes a flash fire or explosion. Liquids found useful under (a) and (b) such as ether, alchohol or white gasolene cannot meet this requirement.

5. The fluid should have good lubricating qualities as lubrication extends the life of pumping equipment.

Recommended Fluids - It has been found that certain fluids have the desirable attributes previously outlined only in narrow specific

pressure ranges. The pressure ranges are presented and the fluids discussed in the following paragraphs.

0-50,000 PSI - Up to 50,000 psi, DTE light or number 10 motor oil is suitable at room temperature. It is so viscous at 60,000 psi and above, it does not transmit pressure readily.

0-150,000 PSI - Either "water white" kerosene or "Plexsol", De-(2 Ethyl-Hexyl) Sepacate, may be used. The latter is preferable because it is a superior lubricant and is non-explosive. Others to be used are an Esso Corporation product, "Unives P-38" or a Hercules Powder Company product, Hercoflex 600. Clean tap water may be used to 130,000 psi at 70°F. It should be rust inhibited with a soluble oil.

0-200,000 PSI - Fluids for use to 200,000 psi are limited to light, small molecule gasoline distillates such as ethyl or methyl alcohol or white gasoline, all explosive. An alternate to these are the glycerine or glycol solutions. All are corrosive to steel and should be rust inhibited.

The glycols are highly resistant to compression and have some lubricating properties. They are never subject to thickening at 170,Kpsi and 70°F.

A fluid recommended for use at 200,000 psi is a glycol inhibited water solution 50% water and 50% ethylene glycol (Zerex or Prestone). This should be well rust inhibited by the addition of a soluble oil 2% by volume. A product recommended is Imminol #517. This is the fluid that will be used in the pressure vessel for the initial extrusion experiments.

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